While the receptive field properties of single neurons in the inferior parietal cortex have been quantitatively described from numerous electrical measurements, the visual topography of area 7a and the adjacent dorsal prelunate area (DP) remains unknown. This lacuna may be a technical byproduct of the difficulty of reconstructing tens to hundreds of penetrations, or may be the result of varying functional retinotopic architectures. Intrinsic optical imaging, performed in behaving monkey for extended periods of time, was used to evaluate retinotopy simultaneously at multiple positions across the cortical surface. As electrical recordings through an implanted artificial dura are difficult, the measurement and quantification of retinotopy with long-term recordings was validated by imaging early visual cortex (areas V1 and V2). Retinotopic topography was found in each of the three other areas studied within a single day's experiment. However, the ventral portion of DP (DPv) had a retinotopic topography that varied from day to day, while the more dorsal aspects of DP (DPd) exhibited consistent retinotopy. This suggests that the dorsal prelunate gyrus may consist of more than one visual area. The retinotopy of area 7a also varied from day to day. Possible mechanisms for this variability across days are discussed as well as its impact upon our understanding of the representation of extrapersonal space in the inferior parietal cortex.

**Keywords:** extrastriate visual cortex, optical imaging, parietal cortex, spatial perception, visual fields, visual pathways

**Introduction**

The inferior parietal lobule of the macaque monkey is comprised of a multitude of visual areas, each of which has neurons with large receptive fields (Steinmetz et al., 1987; Ben Hamed et al., 2001). Various authors have suggested that the inferior parietal lobule plays an important role in the transformation of a retinotopic to an egocentric coordinate system or in the planning of motor movements (Andersen et al., 1990; Stein, 1992; Siegel and Read, 1997b; Previc, 1998; Snyder et al., 1998). For example, retinotopic signals are combined with eye position signals to generate a novel intermediate representation. Studying and comparing the precise visual topography in those areas can clarify the nature of transformation from a retinotopic to an egocentric representation.

Electrophysiological and optical imaging studies have shown that the dorsal prelunate area (DP) and area 7a of the macaque inferior parietal lobule have 'gain fields', i.e. show differential activation with varying angles of gaze (Andersen et al., 1985, 1990; Read and Siegel, 1997; Siegel et al., 2003). Further electrophysiological measurements have been used to demonstrate that the retinotopic location of stimuli is encoded in area 7a neurons (Andersen et al., 1985, 1990; Motter et al., 1987; Read and Siegel, 1997; Merchant et al., 2001). However, none of these studies have demonstrated a topographic organization of retinotopy across the cortical surface, either due to the technical inadequacy of long-term electrical recordings, or due to the intrinsic variability in the distribution of receptive fields. Thus, the retinotopic organization in the upper layers across the two-dimensional surface of the inferior parietal lobule was investigated using intrinsic optical imaging in the behaving monkey for extended periods of time. Intrinsic optical imaging has the advantage that it allows repeated measurements of cortical activity over tens of square millimeters. The mechanism underlying intrinsic imaging is mainly an initial increase in deoxyhemoglobin within the first 3 s of stimulus onset, which leads to decreased reflectance of light at wavelengths in the 500-600 nm range (Malonek et al., 1997).

Optic flow visual stimulation was utilized as it is a powerful cue for spatial location, and area 7a neurons are selective to these stimuli (Read and Siegel, 1997; Siegel and Read, 1997a). Analogous to gain field optical studies (Siegel et al., 2003), it was hypothesized that the position of the stimulus within the visual field should modulate the spatial distribution of the optical signal if the area under study has an orderly retinotopic organization. Areas that possess little or no retinotopy should yield noisy optical maps without systematic variation due to retinal stimulus location.

Single-unit recordings are often used to verify the results of optical recordings (Grinvald et al., 1986; Arieli et al., 1995; Maldonado et al., 1997; Ramsden et al., 2001; Landisman and Ts'o, 2002). Others have shown examples of electrode penetrations through artificial dura (Arieli and Grinvald, 2002; Arieli et al., 2002). While we have confirmed gain fields using a few electrical recordings (Siegel et al., 2003), it is our experience that introducing a low-impedance electrode through the artificial dura leaves a small hole and can damage the underlying pia and cortex due to the presence of a ‘neomembrane’ (Arieli et al., 2002; Chen et al., 2002; Siegel et al., 2003). Avoiding electrode penetration is one factor that has allowed us to optically record up to four years’ data in one animal, enabling repeated measurements of cortical functions. Thus, we needed to see if it was possible to study visual topography optically without using microelectrodes. Areas V1 and V2 were included, as their visual topography is well known. In those areas, the retinotopic organization was confirmed in behaving monkeys with stimuli consisting of elongated vertical stripes near and on the vertical meridian. Appropriate retinotopic activation patterns were also observed with the optic flow stimuli in areas V1 and V2. The study of the inferior parietal lobule (dorsal prelunate and 7a) showed a coarser visual topography across the cortical surface that varied from day to day.

**Materials and Methods**

The intrinsic reflectance signal of the dorsal prelunate cortex (DP) and area 7a was studied in two male rhesus monkeys (Macaca mulatta,
M1R and M2L. Additional recordings were made over areas V1 and V2 posterior to the lunate sulcus. Those areas were exposed within the optical chambers of both animals and served as a control for our methods. The two animals are the same as described in an earlier study (Siegel et al., 2003). All procedures were carried out in accordance with the Rutgers University Animal Institutional Review Board and the NIH Guidelines for the Care and Use of Laboratory Animals.

Surgical Procedures

After the initial training on the fixation task, a head post was implanted. Standard surgical procedures were performed under sterile conditions as described previously (Siegel et al., 2003). The head post was machined from a single stainless steel block with a 50.8 × 25.4 × 6.35 mm mounting surface to provide the exceptional rigidity needed for optical studies (Fig. 1B). The head post was embedded in Palacos orthopedic cement (Smith & Nephew, Richards, Memphis, TN), which in turn was secured to the skull with up to 24 titanium cranio-maxillofacial screws (Synthes, Paoli, PA). In subsequent surgery, a stainless steel recording chamber (20 mm inner diameter) was placed over the inferior parietal lobule based on magnetic resonance images. Within the chamber, a craniotomy and durotomy were performed to expose the cortical surface. An artificial dura was inserted into the craniotomy according to published methods (Shiroyerman et al., 2000; Arieli et al., 2002; Siegel et al., 2003). With this artificial dura covering and protecting the cortex, we were able to collect intrinsic images over a period of >3 years in M1R. In M2L, however, the growth of a neomembrane over the cortex precluded imaging after ~8 months.

Visual Stimuli and Behavioral Task

The monkeys were trained on a detection task that required fixation on a central target. An infrared eye camera (ISCAN, Cambridge, MA) monitored the eye position at 30 Hz; fixation outside the target of

Figure 1. Experimental methods. (A) Stimulus sequence. The trial starts with presentation of the fixation dot in the center of the screen that the monkey has to fixate throughout the trial until reward. The monkey needs to pull the lever back to continue the trial. The optic flow stimulus (expansion flow) is presented in one of nine locations (position –20°, 20° in illustration) on the screen 2000 ms after the fixation point is on. The motion stimulus change from structured optic flow to unstructured motion occurs between 5000 and 7000 ms after fixation point onset; the monkey releases the lever for the reward. (B) Optical imaging apparatus. Left panel: close view of the stainless steel head holder. Once implanted, the lower portion, i.e. the curved groove in the front and the support extending from the back part, is embedded in the cement, but does not touch the skull. The monkey’s head holder is secured with two hardened steel 20¼” screws to a steel plate bolted to a CX-95A carrier attached to a horizontal Newport X-95 beam that provides excellent rigidity. Middle panel: a front view of the assembly on the floating air table including the primate chair in the lower portion of the image. The CCD camera and lenses are in the upper left portion of the image. The monkey’s head is attached to the horizontal X-95 rail in the front. Right panel: a closer view of the camera and lens system, which is secured on a X-26 steel rail that can be slid up and down. This sliding rail in turn is attached firmly to AX-95 devices, whose angle can also be adjusted. Two Nikon 50 mm f1.2 lenses are illustrated. (C) Anatomical location of optical chambers for both monkeys (left, M2L; right, M1R) superimposed on structural MRIs. Within one chamber, two or three exposures were selected: one posterior centered over the lunate sulcus (LS), which included areas V1/V2 and DPv (lower insets with angioarchitectonic maps at 540 nm); and one anterior at the tip of the superior temporal sulcus (STS), which includes areas DP and 7a (upper insets with angioarchitectonic maps at 540 nm). In M1R, a third camera placement slightly further posterior was used to image V1/V2. Scale bar, 2 mm.
1° terminated the trial. A small fixation target appeared in the center of the screen, and the animal continued the trial by pulling a lever attached to the primate chair within a reaction time of 150-800 ms. The monkey maintained fixation on the central target throughout the trial. Two seconds after the trial began, an optic flow stimulus (expansion) was displayed in one of nine locations (3 × 3 grid) centered around the fixation target (Fig. 1A). Two eccentricities (10° and 20°) and stimulus sizes (10° and 20° diameter) for the optic flow fields were used. There were 128 dots per display for the 20° stimulus size and 32 dots per display for the 10° stimulus. The dots all moved radially away from the center of the display at a constant velocity of 6°/s. The monkey had to detect a change in the structure of the stimulus (from structured expansion flow to unstructured expansion), and release the lever within 150-800 ms while maintaining fixation on the central fixation target. The time at which the motion change occurred varied randomly between 3000 and 5000 ms after stimulus onset. A correct response was rewarded with a drop of juice. For most of the experiments, visual topography was mapped using the optic flow stimulus.

In addition, a simpler stimulus was used to verify our ability to obtain fine scale topography in areas V1 and V2 in M1R. Elongated thin bars were presented within the lower contralateral (left) quadrant to map the representation of the vertical meridian. The bar stimulus (1° wide, 12° long) was presented at one of four eccentricities (0°, ±1°, ±2°) centered on the lower vertical meridian, and ±1°, ±2°, ±3° off to the left visual field parallel to the lower vertical meridian; see Fig. 4B). The bar consisted of 128 moving dots that moved at a constant velocity of 6°/s either up or down. Dots in all stimuli had a staggered point life of 532 ms (Siegell and Read, 1997a). While the dots themselves moved, the bar itself was stationary. In this task, the monkey had to maintain fixation and respond to the dimming of the fixation square (0.5° × 0.5°) by releasing the lever. There was no change in the trajectory of the dots. The 10% dimming occurred at random times between 4000 and 5000 ms after fixation onset. In this experiment, a blank condition was included which consisted of the fixation dot alone on the blank screen. Thus, in the elongated thin bar stimulus task, the monkey responded only to the fixation point and his attention was always at the center of fixation.

A blank condition was not used in the optic flow task for the following reasons. In studies of area 7a, evidence was found that the attentional state is important (Siegell and Read, 1997a; Read and Siegel, 1997). To ensure maximal visual responses from the attentional system, and to keep the attentional load consistent, the monkey always attended to the optic flow stimuli. This decision was initially made for the Siegel et al. (2003) optical imaging study and is continued here. If a blank condition were to be used, this would entail displaying only a fixation point to which the animal would direct his attention. A comparison between the blank and the experimental optic flow condition could be made; however, the comparison would not be valid because the effect of the stimulus condition and the attentional state would be confounded.

Intrinsic Optical Imaging

For the optical imaging recordings, the monkey chair and the monkey’s head were attached to a floating air table (Newport, Irvine, CA) via the stainless steel head post, various clamps and an assembly of X95 rails (Newport, Irvine, CA) (Fig. 1B). During data collection the table was floated and the monkey chair did not contact the ground. To stabilize the cortex and dampen pulsations, the chamber was filled with 0.9% sterile saline and hydraulically sealed with a silicon washer and glass window. Images were acquired using the Imaging System (Optical Imaging Co., Rehovot, Israel) with 605 nm illumination, focusing 500 μm below surface vessels. A modified tandem lens system (Ratzlaff and Grinvald, 1991; Siegel et al., 2003) was used to magnify the imaged region. In this lens system, an inverted image in the focal plane of the Nikon 50 mm f1.2 objective lens was imaged by a Nikkor 60 mm macro lens. Alternatively, the Nikkor lens was replaced by an additional Nikon 50 mm f1.2 lens spaced from the camera to act as a macro lens (Fig. 1B). This system permitted a working distance of up to 80 mm and variable magnification. The Imaging System collected 756 × 480 pixel images, which were binned on-line by 2 for the analysis; no other filters were applied to the data. For each stimulus condition, 37 consecutive frames at 7 Hz were collected. Signal-to-noise ratio was improved by trial averaging. Typically, one experiment consisted of 1-3 imaging runs per day, which resulted in 30-90 trials per stimulus position in the optic flow experiment. Approximately 60-100 trials were collected per stimulus position in the elongated thin bar experiment. Image data were collected for all trials, but trials with incorrect responses or artifacts (e.g. excessive motion) were later rejected for analysis (Siegel et al., 2003). Experiments with poor performance or high variability in a plot of the mean to the standard deviation of the optical signal (Siegel et al., 2003) were excluded.

As it was not possible to place the camera and head in identical positions for each experiment, the imaged regions varied slightly from day to day. However, by using the blood vessels as landmarks, the maps for each day were aligned via rotation and translation. This was achieved by superimposing the blood vessel maps in Photoshop (Adobe Systems, San Jose, CA). On the first map of the series of experiments the major blood vessels were outlined and a mask of the vessels was created. The subsequent blood vessel maps were then aligned with that mask using translation, rotation and magnification where appropriate. The parameters from this alignment were then applied to the optical maps.

Chamber Placements

Monkey M1R had a chamber over the inferior parietal lobule of the right hemisphere (Fig. 1C, right). This monkey’s chamber implant and artificial dura proved to be of exceptional stability, and the tissue growth over the chamber was minimal, which allowed us to use the same animal over a period of >3 years using a series of tasks, some of which are reported elsewhere (Siegell et al., 2003). Monkey M2L had a chamber over the left hemisphere in a slightly more posterior location than M1R (Fig. 1C, left). In this animal, a neomembrane grew rapidly and covered the cortex within several months. While this neomembrane was almost opaque to green light illumination, it was sufficiently transparent to red (605 nm) light for 8 months (Fig. 7A) to allow intrinsic imaging and alignment of the larger blood vessels. In both monkeys, areas 7a and DP were exposed within the chamber, as well as early visual areas posterior to the lunate sulcus (LS). Two sections within the optical chamber were targeted, one more anterior location including area 7a and more dorsal portions of the dorsal prelunate (DPl) on either side of the superior temporal sulcus (STS), and a more posterior location on either side of the LS, including V1 and V2 and ventral portions of DP (DPv). (The nomenclature for the DP subregions was chosen to be descriptive; the correspondence with actual visual areas is discussed where appropriate.) Areas V1 and V2 will be referred to as ‘V1/V2’.

Analysis of Optical Imaging Data

As the optical imaging signal develops >2000 ms after stimulus onset, the analysis uses the reflectance signal within the last 2000–3000 ms of the stimulus period (Grinvald et al., 1986; Shtoyerman et al., 2000; Siegel et al., 2003). Baseline normalized single condition maps were always computed to show the individual activation to one stimulus condition. The second half (i.e. 1000 ms) of visual fixation (see Fig. 1A) preceding the onset of visual stimulation was used to normalize the maps. In the elongated thin bar experiment, blank subtraction was also performed. The blank subtraction was computed as the difference in two baseline normalized maps, i.e. the blank condition map (fixation point only) was subtracted from the stimulus condition map (elongated thin bar plus fixation point).

In the optic flow experiments using nine different stimuli, two regression models were used in order to determine the location and shape of the region of the visual field that would activate each pixel. Both models were chosen from the class of general linear models, as these cover the range of receptive field shapes reported in the dorsal stream, and whose parameters can be estimated using closed forms (Read and Siegel, 1997; Anderson and Siegel, 1999). Such an approach was chosen to match the underlying neural retinotopic response as closely as possible by regarding each pixel as a ‘neuron’. Two models were used here. The first was a purely linear model for both the horizontal and vertical position of the stimulus. Such receptive fields have been reported in area 7a (Read and Siegel, 1997). The linear regression was performed independently for each of the 378 × 240 pixels with the equation

\[
D_i(I, f) = z_i(I, f) x_i + z_2(I, f) y_i + b(I, f) + e_i(I, f)
\]
where $D_l(I,J)$ is the $l$th trial's change in reflectance for the $(I,J)$ pixel, $s_x(I,J)$ and $s_y(I,J)$ are the slopes of the regression for the horizontal and vertical coordinates ($x$ and $y$), $b(I,J)$ is the intercept, and $E_l(I,J)$ the error value. To demonstrate the dependence of the intrinsic signal on the $x$- and $y$-position of the stimulus, the angle (in 360° space) and the amplitude of the $x$- and $y$-vectors were computed from the rectangular coordinate system of $(x, y)$. As the optical signal is inversely related to neural activity (Grinvald et al., 1990; Frostig et al., 1990; Shoyerman et al., 2000), all parameters were multiplied by $-1$. The angles were color coded in the functional maps. Thus, each color corresponds to an angle (e.g. 0° or 360°, cyan; 180°, red) within the visual field for which the maximal response would be obtained. To quantify the visual field representation within the maps and to compare them between experiments, regions of interest were selected on the optical maps. Although the imaged region varied between experiments, the same region of interest could be easily located on each map based on the characteristic angioarchitecture. Typically, two locations per cortical region of interest could be easily located on each map based on the maximal response would be obtained. To quantify the visual field representation within the maps and to compare them between experiments, regions of interest were selected on the optical maps. Although the imaged region varied between experiments, the same region of interest could be easily located on each map based on the characteristic angioarchitecture. Typically, two locations per cortical area (50 x 50 pixels, equivalent to $-1.3$ mm) were selected, typically one on the medial and one on the lateral part within the chamber. Large blood vessels were avoided, as they may be modulated by the visual signal (Siegel et al., 2002). Thus, for each region of interest, the average $x$- and $y$-slopes from the linear regression analysis were computed, and the corresponding angle and amplitude of the vector calculated. The resulting angle measurements were analyzed with the circular statistics program Oriana (Kovach Computing Services, Anglesey, UK).

While linear receptive fields have been reported in the parietal cortex, peaked receptive fields were also observed (Read and Siegel, 1997). A linear regression might be thought inappropriate for V1/V2 to model the retinotopic response. Thus, a second model from the class of general linear models was selected for modeling the retinotopic response. A quadratic function (i.e. second-order linear model) has the necessary characteristics with $s_{xx}(I,J)$ and $s_{yy}(I,J)$ as the quadratic coefficients. Its shape can be either a ‘peak’ (or ‘valley’). The width and location of the peak can be evaluated from the regression coefficients. While it is an implicit assumption that visual neurons would encode the position of a stimulus mostly as a peaked function, i.e. a decline in neural activity as the ‘optimal’ stimulus moves away from the receptive field center (Hubel and Wiesel, 1968; Schiller et al., 1976), more complex receptive fields have been reported in the dorsal stream (Motter et al., 1987; Figarev et al., 2001, 2002). Conveniently the quadratic fit accommodates these more complex shapes of retinotopic activation. The signs of the quadratic coefficients determine the shape of the quadratic function (negative, peak; positive, valley). Various combinations of positive and negative quadratic $x$- and $y$-coefficients yield various shapes (peak, valley and saddles). Figure 2 illustrates the various shapes that can be derived from this combination of $x$- and $y$-coefficients.

In order to display these multi-dimensional data, masks were created to reveal the dominant sign of the quadratic coefficient. For each $x$- and $y$-coordinate, it was first determined whether the quadratic coefficient was negative or positive. This allowed the generation of two types of mask (positive, ‘valley’ or negative, ‘peak’) for each data set. For example, an $x$-peak mask displays only those pixels that have a negative sign of the $x$-quadratic coefficient, and masks pixels with a positive sign. The width of the quadratic function is an estimate of the tuning width for stimulus position (Anderson and Siegel, 1999). A large absolute value of the quadratic coefficient corresponds to a narrow peak or valley, whereas a small coefficient indicates a broader tuning. The width of the modeled activated region of cortex was calculated from the equation $X_{50} = \sqrt{\frac{|\beta|}{2|s_{xx}|}}$. $X_{50}$ is the shift in position along the horizontal.

$$D_l(I,J) = s_x(I,J)x + s_y(I,J)y + s_{xx}(I,J)x^2 + s_{yy}(I,J)y^2 + b(I,J) + E_l(I,J)$$

(2)

Figure 2. Illustrative quadratic functions. (A) Negative quadratic coefficients ($s_{xx}$, $s_{yy}$) yield a valley, which was often found in V1/V2. (B) Positive quadratic coefficients ($s_{xx}$, $s_{yy}$) yield a peak. (C) Positive ($s_{xx}$) and negative ($s_{yy}$) coefficients yield a saddle point. (D) Negative ($s_{xx}$) and positive ($s_{yy}$) coefficients also yield a saddle point. $|s_{xx}| = |s_{yy}| = 0.01%/\text{deg}; ||x| = ||y| = 0%/\text{deg}; \beta = 0%$, equation (2).
axis from the quadratic center that results in a 50% change in firing rate from the peak. Similar calculations were made for the vertical coordinate \( y \). Thus, for the selected regions of interest one can also calculate the average width of the activated region along the \( x \) and \( y \) coordinates.

The third aspect of the quadratic analysis is the location of the function’s peak within the two-dimensional \( x \) and \( y \) space. The combination of the linear and quadratic coefficients provides the location of the centers of peaks (or valleys) for each parabola using the equation \(-x_a / 2a_x\) for the horizontal coordinate, with a similar equation for the vertical axis (Anderson and Siegel, 1999). With this formula, the location of the modeled center of activation can be computed within the visual field. Again, these rectangular coordinates are transformed into polar coordinates to create the angle maps. For each region of interest the \( x \) and \( y \) coordinates of the centers are used to locate the preferred visual field location.

Comparison of the First- and Second-order General Linear Models

Both the linear and the quadratic fits were performed for every pixel. This raises the question about which was the better fit. One might simply use the variance accounted for (i.e. the normalized sum square error) on a pixel-by-pixel basis. However, this criterion is flawed, as increasing the number of parameters necessarily increases the variance accounted for (i.e. the \( R^2 \)). Therefore, the addition of parameters needs to be penalized. To compare the two regression models directly, the Akaike Information Criterion (AIC) was used; this balances the number of parameters and residual variance (Akaike, 1974; Siegel and Birks, 1988). For each pixel, the AIC value was computed and the results converted into a binary map where white pixels indicate that the linear model was better, and black pixels indicate that the quadratic model was the better fit.

Results

Behavioral Performance

For the main experiments with the optic flow stimuli, 34 experiments were performed for M1R (21 over V1/V2 and DPv, 13 over DP and 7a); 12 experiments were performed for M2L (7 over V1/V2 and DPv, 5 over DP and 7a). For both monkeys, the percentage correct performance was always >90% for all positions (M1R and M2L, mean 96%). The reaction times for the different retinal locations of the stimuli were analyzed using a stepwise regression analysis (Fig. 3). In M1R, 31 of 34 experiments showed a significant dependence on the position of the stimulus, whereas in M2L, all 12 experiments showed a significant effect of position. The coefficients of the regression were analyzed, and for both monkeys it was found that the fastest reaction times occurred when the stimulus was over the fovea, as illustrated with an experiment for M2L (Fig. 3A, B).

Each monkey’s dependence of reaction time on position was

![Figure 3](image-url)

**Figure 3.** Reaction time data. (A) Single experimental run of 482 trials for M2L (dataset 04/29/2003/gm). Mean reaction time computed for each of nine positions of the 3 x 3 grid (eccentricity 20°). The three curves (crosses, open and filled circles) represent the three different \( y \)-positions (0°, -20° and 20° respectively). (B) Fit for the reaction time data for the experiment shown in (A). The resulting regression is \( RT = -0.482x - 1.962y + 0.364x^2 + 0.228y^2 + 485.6 \) ms. (C) Regression parameters from the stepwise regression for the reaction time data across all experiments and for both monkeys. All values given as mean ± standard error.
similar, with M1R showing slightly weaker effects as evident in the smaller regression coefficients (Fig. 3C). Thus the monkey’s psychophysical performance was reliable and consistent over time within the ranges specified by the defined limits.

**Retinotopic Mapping of Areas V1 and V2 with Elongated Bar Stimuli**

To establish that retinotopic maps could be obtained under the current experimental conditions in the fixating animal, an experiment was performed in M1R using elongated thin bar stimuli defined by moving dots (Fig. 4). It would be expected that a narrow bar in the visual field should result in a band of activation across the cortical surface. With the stimulus centered on the lower vertical meridian, activation was observed ~1–2 mm behind the vessel over the lunate sulcus (Fig. 4A), indeed in an elongated narrow region (Fig. 4C1). This activation pattern is consistent with the known representation of the V1/V2 border along the lower vertical meridian. When the bar was placed ~1° off to the contralateral field, the activation shifted posteriorly (Fig. 4C2). There was also a slight tilt from the 0° activation, probably because the stimuli were not presented within a polar arrangement (as typically used to exploit the conformal map of cortex: Tootell et al., 1988), but rather shifted parallel to the 0° bar. In the subsequent map of the ~2° bar stimulus (Fig. 4C3), the band of activation had moved further posterior so that it was barely visible within the chamber.

Overall, the retinotopic activation from the thin bar stimuli was consistent within and between experiments. This is illustrated in Figure 4D, where the one-dimensional profiles of the percentage change in reflectance signal are shown for two bar locations (0°, D1; ~1°, D2) for three experiments. For the one-dimensional profiles, a section across the cortex was chosen orthogonal to the band of activation for the 0° bar (Fig. 4A,C). Between experiments (i.e. days), the pattern of activation was consistent within and between experiments. This is illustrated in Figure 4D, where the one-dimensional profiles of the percentage change in reflectance signal are shown for two bar locations (0°, D1; ~1°, D2) for three experiments. For the one-dimensional profiles, a section across the cortex was chosen orthogonal to the band of activation for the 0° bar (Fig. 4A,C).

![Image](image_url)

**Figure 4.** Retinotopic mapping of areas V1 and V2 with elongated thin bar stimuli in M1R. (A) Angioarchitectonics obtained at 540 and 605 nm (small inset) showing the large blood vessel over the lunate sulcus (LS) on the top of the image. The posterior edge of the artificial dura is visible on the bottom of the image. The white bar indicates the slice for the profile plots in (D). Scale bar, 1 mm. (B) Stimulus setup for elongated thin bar experiment. The dots move in one direction within the bar window (1° width, 12° height) that is placed at 0°, −1°, −2° or −3° from the lower vertical meridian (contralateral quadrant). (C) Blank-subtracted activation maps shown for three stimulus locations (C1, 0°; C2, −1°; C3, −2°). Scale of gray-level range for all maps shown on the bottom of the figure. Dataset 02/18/2004/r1. (D) Comparison of activation pattern between three different experiments (datasets: 02/17/2004/r1, 02/18/2004/r1, 02/20/2004/r1) with one-dimensional profiles of reflectance taken from the maps for two stimulus locations (D1, 0°; D2, ~1°). The dashed arrows on the two maps (for the 0° bar location, C1; and −1° bar location, C2) indicate the slice for the profile plots as in (A). This experiment was performed 3 years and 11 months after implant of the artificial dura.
very stable with respect to location and amplitude of the signal for both eccentricities. This is evident in the high degree of overlap between the profiles from different days. Consistent results were also obtained within a day’s experiment as demonstrated by splitting the data set in half (not shown).

From the width of the band of activation, an approximation of the cortical magnification factor was calculated. With the stimulus (1° width) at 0° (vertical meridian) the band of activated cortex measured 2.1 mm (at half height). This is consistent with the known cortical magnification factor that ranges between 3.0 mm/deg and 1.7 mm/deg visual angle at eccentricities between 5° and 10°, respectively (see Discussion). The activation from the stimulus centered on the vertical meridian indicated that the V1/V2 border was located ~1-2 mm behind the lunate sulcus in M1R.

**Mapping of Areas V1/V2 and the Ventral Portion of the Dorsal Prelunate Sulcus (DPv) with Expansion Optic Flow**

Recordings from V1/V2 were used to explore the response to large field optic flow stimuli. The responses to these less traditional stimuli were also used to further validate the recording methods. Simultaneously, recordings were collected from the ventral portion of the prelude sulcus (DPv) to determine the presence and nature of its retinal topography to expanding dot stimuli.

**Single Condition Maps**

Single condition maps (baseline normalized) for each of the nine stimulus positions illustrate the primary finding of a variation of the reflected light with the retinotopic position (Fig. 5A). The angioarchitectonics collected at 605 nm illumination from M2L mainly reveal the large blood vessel over the LS with areas V1/V2 posterior and DPv anterior of the vessel (Fig. 7A, see also the inset in Fig. 1C, M2L). The nine single condition maps in Figure 5A demonstrate that in areas V1/V2 relative darkening of the cortex occurs when the stimulus appears in the center (0°,0°) or just below (0°,-20°), as can be seen in the region of interest (black square). The amount of cortex in V1/V2 that is activated is substantial and is not punctuate. This suggests that the point image of the optic flow stimuli covers a substantial portion of the exposed V1/V2 cortex. DPv, on the other hand, was mostly activated by stimuli in the upper right corner (20°,20°), as can be seen in the region of interest (white square). Again large portions of cortex were activated.

**Time Course**

For a selected region of interest (black squares in Fig. 5A), the time course of the optical signal over V1/V2 was obtained for the nine different stimulus locations (Fig. 5B). All time courses began similarly (shaded area between time ~1000 and 0 ms) with a slight increase in the reflectance signal, followed by a decline. This represents a dependence of the reflected light from the initial events of the trial (onset of fixation point, initial saccade to fixation point, etc.). As the maximum visually evoked response peaks at 2000 ms after stimulus onset and either decays or remains constant to 3000 ms after stimulus onset, the intrinsic signal was extracted at this time period (i.e. signal change compared to baseline). Thus, the greatest attenuation in reflected light is found for the center position (0°,0°), followed by the position just below (0°,-20°). A graph of reflected light as a function of retinotopic position indeed shows the minimal response at (0°,0°), as can be seen in the mean reflectance (Fig. 6A). The same style plot (Fig. 6D) was created for a region of interest in DPv (small white squares in Fig. 5A). Here the interpolated maximum was located in the upper contralateral quadrant at (20°,20°).

The baseline-normalized single-condition maps and the region-of-interest graphs therefore show that the optical response depends on the retinotopic position of the optic flow stimulation. Regression models were used to quantify the tuning pixel by pixel for the entire maps and across all experiments.

**First-order General Linear Model (V1/V2)**

A simple linear regression model (equation 1) was first used to quantify these effects (Fig. 6F). This figure shows the region of interest over V1/V2 (black squares, Fig. 5A). The linear fit for the region of interest captures one aspect of the data, i.e. the strength of the lower field response. Note that the regression surface was multiplied by -1 to correct for the inverse relationship between neuronal firing and optical signal. For the entire maps, the process of the linear fit was performed on a pixel-by-pixel basis rather than on single regions of interest and parameter maps were generated. Therefore, each pixel has a regression surface associated with it.

The intercept parameter map A(1,I,y) (Fig. 7B) is the modeled change of the reflected light from the cortex when the stimulus is in the center position (x,y) = 0° in equation 1). In areas V1/V2, the map of the horizontal x-coefficient (a_x) does not show a strong modulation (Fig. 7C), whereas the y-coefficient (a_y) map is dark (negative values) (Fig. 7D). (Note that the brightness of the pixels in the coefficient images indicates the percentage change in signal per degree of visual angle, i.e. %/deg, not the signal amplitude.) The resulting color-coded angle map (Fig. 7F) shows that the V1/V2 cortex is mostly active when the stimulus is in the lower contralateral quadrant (blue-green), in particular along the lower vertical meridian (bright green-yellow), which demarcates the border between area V1 and V2.

**First-order General Linear Model (DPv)**

A regression of the region of interest in Figure 5A (white square) is used to demonstrate the dependence of its signal upon retinotopic position. The resulting regression is a plane with the strongest signal in the upper visual field. A pixel-by-pixel analysis provides the quantification of the optical signal across the cortex (Fig. 7B-F). The activation over DPv is mainly related to stimuli in the upper contralateral quadrant and horizontal meridian (blue colors; Fig. 7F). The amplitude map (Fig. 7E) illustrates that the major blood vessels generate a very strong signal (white pixels), while the strength of the retinotopic signal across the cortex is reasonably uniform. The strong vessel signal could be responsible for the ‘rainbow’-like color change near the LS.

**Second-order Quadratic General Linear Model (V1/V2)**

A linear modulation of stimulus position within the visual field is obviously a poor model for V1/V2. As described in the Materials and Methods, parameters for a second-order general linear model were computed (equation 2). Figure 6C illustrates the quadratic surface for the region of interest (black square in Fig. 5A) in V1/V2. It is a peaked function with its center just below the fovea. In Figure 8, the quadratic regression was computed
Figure 5. Amplitude and time course of 605 nm reflected light as a function of the retinotopic location of the optic flow (eccentricity 20°). (A) Single condition maps over lunate sulcus (location given in Fig. 1C, M2L). Each grayscale image corresponds to the averaged, baseline normalized optical signal for one stimulus location. The stimulus location is noted over each image. For all images the monkey fixated at the primary center position (0°,0°). The small black square over V1/V2 indicates the region of interest from which the time course for (B) was extracted and from which the graphs in Figure 6A–C were derived. The small white square over DPv indicates the region of interest for the graphs in Figure 6D–F. Scale bar, 1 mm. (B) Time course of the baseline normalized optical signal for the nine stimulus locations for V1/V2 matching the single condition maps. Each graph corresponds to one stimulus location. The leftmost shaded region in each graph represents the 1000 ms of the fixation period before stimulus (optic flow) onset. The rightmost shaded region in each graph represents the period during which the optical signal change for the maps (A) and analyses was extracted. Positive deflections indicate an increase of reflected light. Dataset 04/29/2003/gm, M2L.

for the data of Figure 5 on a pixel-by-pixel basis. The first-order coefficients (Fig. 8A,C) are similar to the ones obtained with the linear model (Fig. 7C,D). However, the second-order coefficients provide a quadratic dependency. The quadratic coefficients are predominantly negative over V1/V2, which indicates peaked functions for this area (Figs 2A, 8B,D; see Fig. 6C). The peak centers of the retinotopic activation were computed on a pixel-by-pixel basis for the entire map (see Materials and Methods). For example, the linear x-coefficients (α_x) are mostly positive (Fig. 8A) and the quadratic x-coefficients (α_xx) mostly negative (Fig. 8B), and this yields positive values for the x-centers. The linear and quadratic y-coefficients (α_y and α_yy) are predominantly negative (Fig. 8C,D), which yields negative values for the y-centers. As a result, most x- and y-centers for V1/V2 in M2L are located within the lower contralateral (right) quadrant or close to the lower vertical meridian as shown in the color-coded angle map (Fig. 8E). This is consistent with the known visual topography and with the results from the study with the elongated thin bar stimulus.

Second-order Quadratic General Linear Model (DPv)
While a linear model is perhaps not the best for V1/V2, its appropriateness for DPv is unknown. Figure 6F shows the quadratic fit for the region of interest (white square, Fig. 5A),
which is a saddle shape. The pixel-by-pixel analysis indeed reveals a mix of positive ($\alpha_{yp}$) and negative ($\alpha_{xc}$) coefficients (Fig. 8B,D), which correspond to saddle points (Figs 2C,D and 6F). The DPv centers are also located in the contralateral field closer to the horizontal meridian. However, the modeled retinotopic activation for DPv may be quite complex with a combination of positive and negative quadratic coefficients. Before cataloging the retinotopic activation of the DPv pixels, it was necessary to compare the linear and quadratic models.

Comparison of First- and Second-order Models for Both Imaged Regions

To determine whether the linear or quadratic model was best for each pixel, the AIC was computed. By comparing the resulting scores for each pixel using a binary map, the linear fit proved to be the better model for DPv, while the map over V1/V2 was best modeled by the quadratic function (Fig. 9A). The 'better model' is defined as having a majority of the pixels for that region selected by the AIC. Areas V1/V2 were best modeled as a quadratic function, and DPv as a linear function for 10 of 17 experiments in M1R, and for 6 of 7 experiments in M2L.

To establish which sign of quadratic coefficient was dominant for a particular area, the angle map (Fig. 8E) was overlaid with masks for positive and negative quadratic coefficients ('valleys' and 'peaks'; Fig. 10). Most of the V1/V2 retinotopic activation was best modeled with 'peaked functions' (Fig. 10A,C). This pattern was very consistent for all experiments and both monkeys. In each of the M2L region of interest measurements (total 14; 7 experiments, 2 regions of interest per area, $x$ and $y$), the quadratic terms were negative. In M1R, V1/V2 also had mostly peaked functions, 27 for $x$; 24 for $y$ (total 32, 16 experiments, 2 regions of interest per area). (Although there are saddle points in the DP regions, these are not the appropriate model for the data, as the linear regression was selected by the AIC.)

**Summary of Retinotopic Organization in V1/V2 and DPv**

To quantitatively assess the retinotopic organization of the optical signal across experiments, regions of interest were selected medially and laterally within one area. Within selected regions of interest, the width of the peaked function for V1/V2 was calculated to provide an estimate of the modeled width of retinotopic activation (see Materials and Methods). In M1R, with the 20° stimuli the average width was $24° \pm 2.75°$ (mean $\pm$ standard error), $n = 14$. For the smaller 10° stimuli, which were also presented closer to the center, the average width was $38.6° \pm 6.1°$, $n = 18$. The difference between the two stimulus sets was not significant ($t = -1.97$, df = 30, $P > 0.05$). In M2L, the average width of retinotopic activation was $15.8° \pm 10.1°$, $n = 12$ for the 20° stimulus, and $11.3° \pm 9.9°$, $n = 2$ for the 10° stimulus ($t = 0.58$, df = 12, $P > 0.05$).

Similar to the single example for M2L (Figs 5–7), all the regions of interest selected in areas V1/V2 consistently showed preference for stimuli in the lower contralateral visual field and along the lower vertical meridian using the second-order model.
This was also the case for monkey M1R (Fig. 12A). This preference for a particular angle was confirmed using the Raleigh test for uniformity in both animals (Zar, 1984). The Raleigh test is a circular statistic that tests whether there are significant deviations from a uniform distribution. The null hypothesis of a uniform distribution of directions was rejected ($P < 0.05$). This finding confirms that the retinotopic activation was consistent across experimental sessions (days) and matches the results using the elongated bar stimuli. Hence the values of mean direction and the confidence interval provide a meaningful summary of the tuning for the region of interest (Fig. 12A).

The DPv data were also tested for uniformity and were found to be uniform for both animals ($P > 0.05$). This indicates variability in the measurements across days with our stimulus paradigm as evidenced by the high circular standard deviations (Fig. 12B).

**Mapping of the Dorsal Portion of the Dorsal Prelunate (DPd) and Area 7a with Expansion Optic Flow**

In both animals, the draining vein, which lies between the dorsal apex and the dorsal-most portion of the STS, was used to divide DPd and area 7a (Fig. 1C, insets; Fig. 11A). The regression parameters were estimated for both the first- and second-order models. The two models were then compared using the AIC. For DPd and area 7a, the retinotopic activation was always best modeled by a linear function (Fig. 9B). A typical example of such an experiment is presented in Figure 11 for M1R. The image of the angioarchitecture under green light (Fig. 11A) shows a clear view of the cortex without any signs of neomembrane growth. The intercept ($\beta$) and amplitude maps (Fig. 11B,E) indicate that strong signals originate from the blood vessels. The optical signal amplitude over cortex free of large blood vessels appears relatively even. The map of the horizontal coefficient ($\alpha_x$, Fig. 11C) shows modulation from lateral (light, positive values) to medial (dark, negative values) in area 7a, whereas the vertical coefficient ($\alpha_y$, Fig. 11D) map appears rather uniform. The DPd cortex also shows modulation along the $x$-axis with mostly dark pixels (negative values). This is summarized in the colored angle map (Fig. 11F), where the purple and dark blue colors suggest an emphasis on upper contralateral activation both in DPd and 7a.

Raleigh's test for uniformity was applied for the DPd and 7a angle data for the regions of interest for both animals. DPd was significantly non-uniform in both animals (M1R, $P < 0.01$; M2L,
P < 0.05; Fig. 12C), whereas area 7a in both animals showed uniform distributions (Fig. 12D), as suggested by the large standard deviations. Thus, the regions of interest in DPd had repeatable retinotopic representations while nearby area 7a did not. The retinotopic representation of DPd was different for the two hemispheres in the two animals, with one predominantly in the upper visual field (M1R) and one in the lower visual field (M2L).

Figure 8. Retinotopic maps from quadratic regression analysis. (A) Map of linear x-coefficient $\alpha_x$. (B) Map of quadratic x-coefficient $\alpha_{xx}$. (C) Map of linear y-coefficient $\alpha_y$. (D) Map of quadratic y-coefficient $\alpha_{yy}$. (E) Direction of centers of retinotopic activation in polar coordinates. The center of the saddle, peak or valley of the quadratic function was calculated for each pixel in the optical image from the regression coefficients (see Materials and Methods). The resulting color-coded angle map shows the location of these centers transformed into polar coordinates. The range of the grayscale is shown below each pair of linear and quadratic coefficient maps. Dataset 04/29/2003/gm, M2L.

Figure 9. Comparison of the quadratic and linear fit with the Akaike Information Criterion (AIC). Black pixels indicate that the quadratic regression provides the better fit; white pixels indicate that the linear regression is better. (A) AIC analysis from V1/V2 and DPv example, as shown in Figures 5–8, demonstrates that V1/V2 contains mostly black pixels (except for the larger blood vessel), suggesting that the quadratic model is better, whereas DPv contains mostly white pixels, indicating that the linear fit is better (dataset 04/29/2003/gm, M2L). (B) AIC analysis from DPd and 7a example, as shown in Figure 11, shows that in both areas white pixels dominate indicating that the linear model is better (dataset 03/31/2000/gm, M1R).
Discussion

Intrinsic optical imaging was utilized for mapping retinotopic organization in striate and extrastriate parietal areas in behaving monkeys. The validity of the stimulus and recording method was established by imaging early visual cortex with its known retinotopy. Two stimulus types (elongated thin bars and larger circular expansion optic flow) were used in V1/V2, and results from both agreed with the known visual topography. Areas of the inferior parietal lobule were then tested for retinotopic organization with optic flow stimuli.

Selection of Model for Quantitative Mapping of Retinotopic Activation

Regression models were used to reduce and summarize the large amounts of optical imaging data. Two general linear models were used to model the dependence of the optical signal upon the stimuli; each pixel was modeled independently. This approach permitted a direct numerical comparison of a first-order linear model and a second-order quadratic model. An alternative choice to the second-order quadratic is an exponential Gaussian model, which is commonly used to represent receptive fields in single-unit data (Ben Hamed et al., 2001). Like the second-order quadratic, the receptive field width and center can be computed from the Gaussian model coefficients. However, the determination of the coefficients of the Gaussian model must be performed by numerical gradient descent methods or annealing to minimize an objective function. This is further complicated by the necessity to compute a DC offset (i.e. the signal at the extreme edges of the receptive field.) While various powerful minimization methods are currently available, there is no guarantee that the global minimum, and hence the best fit to the data, will be obtained. Therefore the general linear model, with its closed form solutions, was selected. Further, the general linear model had the advantage of direct comparison with previously published results from single-unit recordings (Andersen et al., 1990; Read and Siegel, 1997).

Time Course of Signal During the Fixation Period

In the present study, there was a variation in the optical signal that occurred after the initial fixation onset. This type of change was seen in each of the areas recorded reported here as well as in Siegel et al. (2003). In V1 of anesthetized animals, such variation is not reported (Shtoyerman et al., 2000). In one published figure of a time course for V1 of behaving monkey (Grinvald et al., 1991), the fixation event is not shown, as the monkey was passively viewing the display. In the other figure (Fig. 4 of Shtoyerman et al., 2000), the baseline is flat during the initial fixation period. That Shtoyerman et al. (2000) do not report the modulation during the initial fixation period may be because the time course of their data is normalized by the time course of a blank condition that might also vary in time. As the time course in the current study is not normalized by a blank condition, the modulation of signal during the initial fixation period is thus revealed. It could be due to a number of events that occur during the start of a trial. The fixation point is illuminated, the monkey makes a saccade and there are shifts in attention. The ‘baseline normalization analysis’ described in the Materials and Methods was thus used to ensure the stability of the data over the duration of the trial and allowed us to avoid using a normalization procedure with a ‘blank’ condition.

Validation of Method in V1/V2

As electrophysiological recordings compromise our optical imaging, two different measurements were made in areas V1 and V2 to establish the validity of the optical imaging method.
and the choice of stimuli. First, areas V1 and V2 of M1R were mapped with elongated bar stimuli placed along the lower vertical meridian at increasing eccentricities up to 3° away from the meridian. Many researchers have used intrinsic optical imaging to reveal retinotopic organization in visual cortex in various anesthetized species (McLoughlin and Blasdel, 1998; Macknik and Haglund, 1999; Blasdel and Campbell, 2001; Bosking et al., 2002; Lyon et al., 2002; Schiessl and McLoughlin, 2003). To our knowledge there is only one imaging study, using voltage-sensitive dyes, that has examined retinotopy in the behaving monkey (Slovin et al., 2002). Our experiments demonstrated that primary visual cortex is sensitive to slight spatial displacements of a line or band stimulus, and that these topographically organized responses can be reliably visualized by optical imaging. This was confirmed with intrinsic imaging in the behaving monkey with the current elongated thin bar experiment that showed consistent activation along the V1/V2 border when the stimulus was centered on the lower vertical meridian. The results from this experiment are also consistent with previous electrical and 2-deoxyglucose studies (Gattass et al., 1981; Dow et al., 1985; Tootell et al., 1988) as well as with the cited optical studies of retinotopy in macaque monkey V1 and V2. To the best of our knowledge, the present study is the first intrinsic optical recording of retinotopy in behaving monkey V1 confirming the anesthetized optical studies and the voltage-sensitive dye imaging study (Slovin et al., 2002).

The present study did not observe a mirror-image representation of the −1° or −2° bar in V2. There are a number of reasons for this. First, V2 in the monkey may start too close to the lunate sulcus to be imaged. Further, V2 cortex curves down into the lunate sulcus so that the imaged cortex becomes out of focus or unobservable. This can be seen on the blood vessel map that becomes out of focus anterior to the V1/V2 border. It is also possible that the stimuli consisting of small moving dots were not ideal for activating area V2. The superficial layers of V1 contain many neurons (up to 30%) that prefer small stimuli (‘end-stopped cells’), whereas in V2 no such differences were reported between laminae (Heider et al., 2000). Further, optical imaging studies of V1 and V2 (Roe and Ts’o, 1995; Xiao and Felleman, 2004) suggest a highly complex mapping across V2.

Reliable and reproducible retinotopic activation was obtained with the elongated thin bar stimuli, consistent with the known retinotopy and cortical magnification factors. The representation of the elongated bar stimulus across the cortical surface was fine enough to establish that millimeter scale features could be recorded with our system in behaving monkey. The activation

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**Figure 11.** Angioarchitectonics and retinotopic maps for DPd and area 7a from linear regression analysis. (A) Angioarchitectonics imaged at 540 nm showing the large draining vein covering the caudal end of the superior temporal sulcus (STS). This experiment was performed 2 weeks after implant of the artificial dura. Conventions otherwise as in Figure 7. Scale bar, 1 mm. Dataset 03/31/2000/gm, M1R.
of reasons. First, there is a dearth of studies examining the response of neurons in these early visual areas to optic flow. Second, optic flow stimuli are extensively used for studying extrastriate cortex. Third, it is not known a priori whether large field optic flow stimuli can be used to extract retinotopic organization in V1/V2 or elsewhere.

In the current optical imaging study, much of the imaged cortex was modulated for each stimulus location, indicating that the expansion optic flow stimuli had a large cortical point image. Small millimeter and submillimeter point images, as typically seen (Macknik and Haglund, 1999; Blasdel and Campbell, 2001; Bosking et al., 2002), were not observed with the $10^\circ$ or $20^\circ$ optic flow stimuli. The inability to record fine scale changes across the cortex appears not to be a technical limitation, as we can observe finer scaled structures in V1 with the elongated thin bar stimuli. The activation of a substantial portion of the imaged cortex by the optic flow stimuli appears to be a substantial and repeatable finding. Even though much of the cortex was activated by any one of the nine stimuli, the differences in activation between each stimulus, as evident by inspection of the single condition maps or by the regression methods, could be extracted and analyzed to yield a retinotopically based representation of the visual field on a pixel-by-pixel basis. It was clear that the central and lower contralateral stimuli best activated the V1/V2 cortex. This is consistent with previous multi-unit mapping (Gattass et al., 1981) and imaging studies (Blasdel and Campbell, 2001; Brewer et al., 2002; Fize et al., 2003) using more classical stimuli, as well as with the results using the elongated thin bar stimuli described herein.

In order to extract the retinotopic organization from the expansion optic flow signals, two general linear models were used. The AIC portion of the analysis selected the quadratic as the better fit of the two models. The signs of the quadratic terms were mostly negative, which corresponds to a peaked function of the retinotopic activation, which is consistent with previous electrophysiological mapping studies of areas V1 and V2 (Hubel and Wiesel, 1968; Schiller et al., 1976).

By using the quadratic regression coefficients and intercepts within any given region of interest, an estimate of the average retinotopic activation width could be computed. This modeled width corresponds to the region of the visual field for which a particular pixel or region of interest was activated. Surprisingly, the modeled width was fairly large ($11^\circ$–$39^\circ$) for V1 where single receptive fields are often $<1^\circ$, especially in superficial layers of area V1 (Hubel and Wiesel, 1968; Schiller et al., 1976; Heider et al., 2000).

There are a number of possible explanations for this discrepancy between receptive field sizes of V1 neurons and the scale of the retinotopic activation. First, it may be that the $10^\circ$–$20^\circ$ size of the stimuli yielded a large point image on the cortex. Second, the optic flow stimuli were presented peripherally (at $10^\circ$–$20^\circ$ eccentricity) and may not have properly stimulated the exposed portion of V1/V2. The exposed cortex within the chamber most likely represents eccentricities between 5$^\circ$ and 9$^\circ$ (Gattass et al., 1981). Calculations of the cortical magnification factor confirm this assumption. The known formula of the cortical magnification factor along the vertical meridian is $\text{CMF}^\circ = 0.07 + 0.052E$, where $E$ is the eccentricity in degrees of visual angle (Tootell et al., 1988). A $10^\circ$ radial stimulus presented in the center of the fixation would activate $\sim 13$ mm of cortex if the cortical surface represented eccentricities between 5$^\circ$ and 10$^\circ$. For a $20^\circ$ radial stimulus, the activated pattern obtained with the bar stimuli confirmed that our optical imaging approach can be successfully utilized to measure retinotopic activation in the behaving monkey, and thus serves as a basis for subsequent studies using optic flow in visual association cortex. The reliability of these V1 results also suggests that the variability of activation that we describe in other visual areas does not arise from inadequacies in the optical imaging method.

A second approach to validate our methods was to map V1/V2 with optic flow stimuli. Optic flow was selected for a number

Figure 12. Summary of visuotopic organization from regions of interest within each area studied, shown separately for each monkey. Mean angles for each region of interest are shown as circular histograms with the concentric circles representing frequency increments of 1. Note that the two monkeys have different scales. Angle measurements were taken for two regions of interest per area and per experiment (M1R: V1/V2 and DPv, each $n = 32$; DPd and 7a, each $n = 26$; M2L: V1/V2 and DPv, each $n = 14$; DPd and 7a, each $n = 10$). For M2L, the right hemifield is contralateral, for M1R, the left hemifield is contralateral. The circular error bars indicate the 95% confidence interval. The numbers on the bottom of each circular plot show the mean angle ± standard error for each area and monkey. Each pair of panels A–D represents one area (V1/V2, DPv, DPd, and 7a respectively). The retinotopic representation (peak centers) for V1/V2 was obtained with the quadratic regression (better fit confirmed with AIC analysis). For the DPv, DPd, and 7a panels, the linear regression provided the retinotopic location of directional vectors within selected regions of interest.
cortical area representing 5°–20° eccentricities would measure ~25 mm. Thus, considering that the field of view in the current study was maximally 10 mm wide, the entire cortex exposed within the chamber would be activated by a 10° or 20° stimulus. Thus, it is not surprising that mostly the center stimulus activated much of imaged V1/V2, as was expected from the cortical magnification factor calculations.

A third reason for the substantial area of cortex activated by the expansion optic flow is that the optical signal has a substantial contribution of small diameter subthreshold elements as well as spiking somas (Das and Gilbert, 1995; Toth et al., 1996; Logothetis et al., 2001). These subthreshold neuronal changes can alter the metabolic responses providing a measure of the subthreshold representation of the visual field. Fourth, these effects might be synergistically emphasized by the non-classical nature of the optic flow stimuli (Hammond and MacKay, 1977; Allman et al., 1985; Knierim and Van Essen, 1992; Albright and Stoner, 2002). There may be substantial lateral interactions that spread out the point image with the expansion flow stimuli. Thus, it appears that the large area of cortical activation could be explicable in terms of the large stimulus size, the peripheral cortical representation under study, subthreshold small diameter elements and the nature of the expanding optic flow.

Although the point image was large, the centers of activation on the cortex appear in the appropriate positions for the optic flow stimuli and elongated thin bar stimuli. The experiments on the V1/V2 exposure with its well-known retinotopic organization therefore validated our approach that optical imaging in conjunction with the radial optic flow stimuli can be used to reliably map the visual field organization. As the source of the optical signal should be similar in extrastriate cortex and striate cortex, it seems reasonable to expect that the measurements obtained in inferior parietal lobule should provide a reasonable estimate of the visual topography.

**Lack of Retinotopy in DPv**

Within the same exposure and set of experiments as V1/V2, the cortex anterior to the lunate sulcus labeled DPv was imaged. This experimental design allowed a simultaneous comparison of the representation of these two areas. It was expected that the retinotopic activation of the DPv cortex ought to be larger than those of V1/V2; confirmation of this was provided by the finding of a linear dependence on stimulus position. Optical responses could be obtained for stimuli across the entire visual field, whereas the V1/V2 responses were limited to the lower contralateral quadrant. The optical response in DPv was better fit with a linear model as opposed to a quadratic model as in V1/V2. This suggests that the modeled retinotopic activation in DPv did not show a clear localized modulation with stimulus position (i.e. localized maxima), as was the case in early visual cortex, and that the underlying receptive fields were very large (e.g. bilateral).

Within each day’s experiment, retinotopic topography could be obtained for both DPv and for V1/V2. What was surprising and different about these DPv measurements was the lack of reproducibility of the retinotopic activation from day to day as compared to the V1/V2 measurements, which were reproducible. The high variability was quantified as a statistically uniform distribution of the preferred angles within regions of interest across days. In the same data set, the V1/V2 activation yielded a non-uniform distribution. As the measurements in the two areas were obtained simultaneously, and thus the behavioral and experimental conditions were identical, it is likely that the lack of reproducible activation in DPv was not a result of noise in the measurement system and indeed represents the variable state of DPv across days. There may be a genuinely variable relationship between visuotopic representation and the cortical activation within this particular area.

If it is not due to noise in the measurement system, then four other possible sources can be outlined to account for the lack of consistent retinotopy in DPv from day to day. First, it is possible that this part of the cortex does not respond to optic flow stimulation, and that the weak response masks a retinotopic organization. However, the optical signals recorded here were indeed dependent on the retinal position of the stimulus. The strength of the optical signal to optic flow in DPv was comparable to those recorded elsewhere in the chamber, suggesting that this region does indeed respond to optic flow.

Second, it is possible that extraretinal influences, e.g. attentional (Mountcastle et al., 1987; Cook and Maunsell, 2002) or oculomotor signals (Fischer and Boch, 1981; Fischer et al., 1981; Tolias et al., 2001; Rosenbluth and Allman, 2002), modulate the retinotopic signal. As the monkeys in the present study had to detect a change in motion in various locations within the visual field while maintaining fixation, it is likely that spatial attentional processes were involved. While the monkeys’ performance was consistent within preselected ranges (i.e. percent correct trials, reaction times), there could be some covert variation within the acceptable range of behaviors that could account for the modulation in the retinotopic maps. Various studies clearly show that attention modulates single-cell firing rate in prestriate cortex, in particular in area V4, and that this modulation can be either facilitatory or inhibitory (Motter, 1993; Luck et al., 1997; Bender and Youakim, 2001).

Third, it may be that the variation in the signal is indicative of variability in the afferents to DPv. Optical signals at 605 nm, similar to the blood oxygenation signal (i.e. BOLD) in functional magnetic resonance imaging (fMRI), probably arise from the small presynaptic and dendritic elements in the upper layers (Logothetis et al., 2001). In early visual areas such as V1, there is ample evidence that there is a columnar organization with a fixed visual topography. Here the optical signal may well correspond with the single-unit signals. However, the columnar organization of DPv is not established, and the upper layer signals could indicate feedback signals from projective areas. Thus, there may be variability in the upper layer optical measurements that may not necessarily match layer IV inputs.

Additional experiments will be needed with simultaneous optical and electrical recordings to examine this explanation for the variation in the retinotopic activation over time.

Finally, the variability may arise from ongoing cortical dynamics and plasticity (Pons et al., 1991; Arieli et al., 1996; Buonomano and Merzenich, 1998; Crick and Koch, 2003). If the cortical circuitry responds differently over time, e.g. with variable spontaneous activity, or if the animal’s experiences outside the recording apparatus can modulate the cortex, then the retinotopic activation could change over time.

The literature does not appear to contain any single-unit data that either conflict with or support the variation in retinotopic organization in DPv over days. Tangential recordings made in the behaving monkey with single units over time (Pigarev et al., 2001, 2002) do permit the description of topography from a few locations within one penetration within a single day. However, no evidence was presented in these studies that the same...
position of cortex had the same receptive fields for two days. Their finding of a progression within one day’s penetration would be consistent with the optical data presented here. While an fMRI study in the awake monkey demonstrates topography across the entire prelu nate region, the resolution is insufficient to determine whether there are variations in topography on the scale of a few millimeters as described here (Fize et al., 2003). Furthermore in both the electrophysiological and fMRI studies, the task was very different with the monkey closely attending to a central fixation point and ignoring the test stimuli.

The primary comparison that can be made with published single-unit data concerns the nature of the receptive fields reported from the electrical recordings. The optical data present pixels with retinotopic activation that extend into both hemispheres. Both large full field contralateral and bilateral receptive field organization has been reported over multiple experiments with electrical measurements (Maguire and Baizer, 1984; Pigarev et al., 2001). Taken together, these findings suggest that DPv responded quite differently from V1/V2, with larger retinotopic activation and more variable retinotopic organization across days.

Retinotopic Organization of DPd

Recordings were made from a second camera location over the dorsal DP and area 7a. The experimental design was again intended to permit a direct comparison of two areas. The DPd region was best modeled with the linear regression — meaning that the retinotopic activation by definition extended across both hemispheres (upper or lower). Across the days of study, the retinotopic topography in both monkeys was found to be consistent for each animal. In M1R, upper visual field was best represented, while in M2L, lower visual field was best represented.

The difference in the upper and lower retinotopic representations between the two animals studied indicates either a hemispheric difference or individual animal variability. There is nothing in the current data to select one explanation over the other. However, it is interesting to note that the gain field representations of M1R and M2L are known (Siegel et al., 2003); for both animals the gain fields for DPd are for the upper eye positions. (DPd is referred to as DP in the earlier study.)

Comparison of DPd and DPv

There were a number of differences between DPv and DPd. Unlike DPv, the more dorsal aspect of the prelu nate cortex showed a consistent retinotopic organization across days. With the presumption of DP being one cortical area, these findings seem paradoxical. However, if the imaged cortex on the prelu nate gyrus comprises more than one area, then different retinotopic organization could be expected. Thus, cautious use of the nomenclature seems necessary here.

DPd certainly corresponds to area DP as presented by Andersen et al. (1990). The exact identity of DPv remains open. It may be the same as that described by Pigarev et al. (2001). As the precise location and anatomical organization of areas on the prelu nate gyrus is not yet known, it is not clear precisely which areas are exposed within the recording chambers. An inhomogeneity in visuotopic organization that centers on a representa tion of the vertical meridian running across the prelu nate gyrus has been described (Maguire and Baizer, 1984; Youakim et al., 2001). Does this vertical meridian represent a border between two distinct areas? The existence of a complex of visual areas within the optical recording chamber remains the best description of the DP areas imaged here. This conclusion is supported by electrophysiological studies that report an increasingly heterogeneous receptive field organization and increasing receptive field size and eccentricity as one moves from lateral to medial locations on the prelu nate gyrus (Maguire and Baizer, 1984; Tanaka et al., 1986; Gattass et al., 1988; Pigarev et al., 2001; Youakim et al., 2001; Pigarev et al., 2002).

One final speculation is that the entire ‘retinotopic’ mapping for DPd described here is actually a result of shifts of attention and not directly related to the sensory input. While this is unlikely given the known sensory properties of area DPd evaluated with single-unit technique (Tanaka et al., 1986; Andersen et al., 1990; Pigarev et al., 2001, 2002), we cannot completely discard attention as the primary mechanism creating the intrinsic optical maps reported here. However, preliminary data, in which identical visual stimuli are presented and attention is shifted explicitly, suggests that attentional maps have very different qualities from those reported here (Raffi and Siegel, 2001).

Lack of Retinotopic Organization in Area 7a

The optical recordings in area 7a showed a retinotopic organization within each day. The retinotopic activation was best modeled as a linear function but the topography was not statistically reproducible across days. The consistent visual topography recorded in the same chamber from area DPd rules out methodological causes for the variability across days. Furthermore, area 7a recorded from the same two animals had a consistent lower gain field representation (Siegel et al., 2003).

Electrophysiological studies examining retinotopic organization in area 7a show large bilateral fields (Motter and Mountcastle, 1981; Motter et al., 1987; Andersen et al., 1990; Blatt et al., 1990; Read and Siegel, 1997; Merchant et al., 2001). Thus, the receptive field structure in these studies is consistent with the estimates of the portion of the visual field represented by a pixel in the optical data.

There are no electrophysiological data indicating whether the receptive field topography is constant across days in the behaving monkey. However, it is known that that the receptive field shapes can change within a single recording session as a function of the stimulus or attentional paradigm (Bushnell et al., 1981; Read and Siegel, 1997; Constantinidis and Steinmetz, 2001). For example, different receptive field maps were collected depending on whether small squares or optic flow stimuli were used (Read and Siegel, 1997). When the squares were presented, the animal attended to the central fixation point; when optic flow was presented, the animal attended to the change in motion structure. If such changes were to occur across the entire population of neurons based on covert changes in attention, then there might be complete reorganization of the receptive field map topography. (A similar explanation in covert attentional shifts or shifts in strategy across days was discussed with respect to the DPv data.) Experiments which specifically address shifts in spatial attention are needed to test this hypothesis directly. Alternatively, there might be an orderly retinal topography in area 7a, but only found in deeper layers. One possible route for retinal topography to arrive in area 7a would be from known anatomical projections of DPd to layer IV of area 7a (Cavada and Goldman-Rakic, 1989; Andersen et al., 1990).
The Relationships Between Area DPd and Area 7a

The differences obtained in the retinotopic organization between DPd and 7a — with area 7a lacking reproducible retinotopic organization, and DPd containing reproducible topography — is striking considering that gain field tuning obtained for eye position is reproducible in both areas. In these same monkeys, area 7a has lower eye position gain fields and DPd has upper eye position gain fields. The gain fields of area 7a and DPd are not continuous at the blood vessel that runs between them even though there is no sulcus at that location. This result has been interpreted to suggest that these two areas share their representation of gain fields (Siegel et al., 2003).

It is important to emphasize these differences between 7a and DPd. The large blood vessel is an arbitrary boundary that has demarcated gain field differences in area 7a and DP (Siegel et al., 2003). That study was unable to determine if the two regions were indeed two separated areas or if they formed one area. Multiple determinants define a cortical area (Van Essen, 1985); one of them is the retinotopic organization. The finding of differences in retinotopy between the two areas adds weight to the conclusion that these are indeed two separate areas that share some functions.

It is worthwhile to reconsider the organization of the crown of the posterior parietal lobule. These data are the first indication that area 7a and DPd split the labor of representing gain fields, while 7a forgoes a static retinotopic organization, at least as far as can be obtained from the upper layers using optical imaging. This may indicate that area 7a is more plastic in response to demands of spatial perception and attention.

The identification of specific mechanisms for the changes in the retinotopic organization between closely situated DPd and 7a via known anatomical projections (Andersen et al., 1990) may prove extremely valuable in clarifying the mechanisms of plasticity. Additional studies using tasks designed to assess attention are underway (Raffi and Siegel, 2001, 2003) to elucidate the functional overlap and interactions between these two portions of cortex. The discovered variability in representation may prove essential to explain how a physically small area of parietal cortex can subserve so many spatial functions, e.g. attention, intention or optic flow representation. Lastly, plasticity of representation in this region of cortex would be extremely useful for adaptation to alteration in body size with growth and to varying environmental and behavioral demands.

Notes

Discussion of this work with M. Raffi and K.F. Ahrens is recognized, as is further development of the macro-lens system by K.F. Ahrens. The MRI reconstructions provided by R.E. Phinney are appreciated. Technical assistance of J.A. Siegel, R.E. Meltzer and D. Dimichino in the experiments is appreciated. The initial gift of the artificial dura from A. Arieli and A. Grinvald is gratefully recognized, as is their assistance in the early stages of this study. This work was supported by the Whitehall Foundation, National Institutes of Health Grants EY-09223 and 1S10RR-12875, National Science Foundation Grant: National Partnership for Advanced Computational Infrastructure RUT223, and the Hungarian Scientific Research Foundation OTKA/T023657 (GF). The massive file transfer and storage services provided by the Storage Resource Broker team at the San Diego Supercomputer Center are appreciated, as is the attentive assistance of the team manager George Kremenek.

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